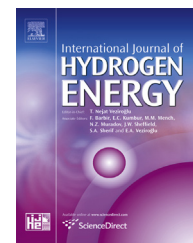


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Steam co-gasification of coal and biomass – Synergy in reactivity of fuel blends chars

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ABSTRACT

Development of clean coal technologies is the answer to increasing energy demand and environmental concerns related to conventional coal processing technologies. The technologies of fossil fuel gasification are technically proven and commercially available. Attempts of utilization of waste materials and renewable energy resources in gasification-based energy generation systems has been made, but wide application of such systems is still hindered by issues inherently combined with the characteristics of the materials. These include discontinuous supplies of a fuel of limited resources and varying composition resulting in poor economy of small-scale systems and operating problems related to tars formation and corrosion, especially when biomass utilization is considered. In the light of the above co-gasification seems to offer several advantages through mitigation of undesired effects of both carbon-intensive utilization of coal and low efficient and troublesome operation of biomass/waste-fed gasification systems. The experimental results presented in the paper address the issues of determination of potential synergy effects resulting from the utilization of fuel blends composed of materials of various physical and chemical characteristics, which are still insufficiently discussed in the literature, especially when hydrogen-rich gas production in co-gasification is concerned. The results of reactivity tests of fuel blends of coal and energy crops biomass in the process of steam co-gasification in a laboratory scale fixed bed reactor at 700, 800 and 900 °C are given proving the synergy effect in co-gasification reflected in increased reactivity of fuel blends when compared to coal and biomass chars reactivity under similar process conditions.

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1. Introduction

Conventional processes of thermochemical conversion of solid fuels, especially coal, are significant sources of emission of air contaminants like particulates, carbon dioxide, sulfur and nitrogen oxides. Since they still represent a substantial

proportion of energy generation processes, development and implementation of clean coal technologies is of special relevance, particularly in countries with energy sector based on coal. These environmentally friendly technologies include gasification of significantly lower emission levels and higher efficiency than combustion technologies. Gasification reactors

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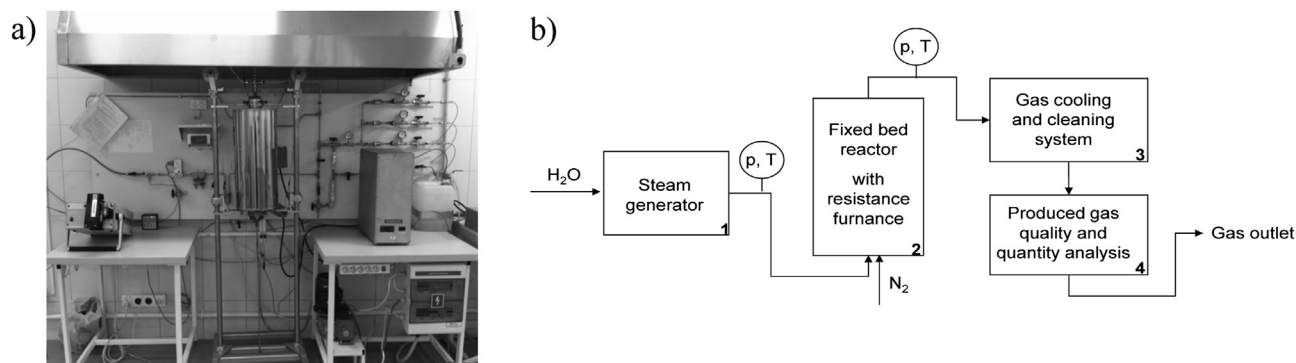


Fig. 1 – Laboratory scale fixed-bed reactor installation: a) view and b) schematic diagram.

has been commercially available for decades and synthesis gas has been widely utilized in chemical and petrochemical industries, and recently also in power generation [1–4]. Total world synthesis gas capacity is approximately 71,000 MW_{th} and is expected to increase of 71% by 2016, with coal as the main fuel (over 60% of synthesis gas capacity in 2016) [1]. Utilization of biomass, as a zero emission energy source, in gasification systems is still marginal and hindered for several reasons. First, the limited supplies of biomass result in a relatively small scale of gasification systems and therefore the unit prices of energy generated are high. Second, there are still many technical aspects to be solved to ensure smooth operation, to begin with a need for special design fuel feeding systems, biomass pretreatment (drying, torrefaction), to end with tars formation and corrosion mitigation. This makes biomass gasification still less efficient and economically competitive than fossil fuels gasification [5–7]. In this light co-gasification offers an attractive option of combining stable, in terms of volume and quality, supplies of a primary fuel – coal, with utilization of zero emission fuel – biomass, resulting in improved efficiency, economy and environmental benefits. Numerous research works have been reported recently on application of various fuel blends, including coal and biomass, and concerning biomass pretreatment, optimization of blend composition, feeding system, catalysts and operating parameters of pyrolysis and gasification processes in various reactor and system configurations [8–19]. In some of them various synergy effects in co-pyrolysis or co-gasification are indicated [20–32], including synergy effects in reactivity [33–36], but recognition of the mechanisms behind the phenomena observed needs further detailed studies [8,34]. This is especially relevant to hydrogen-rich gas production in co-gasification, since the data on the process is very limited [22,23,37–40].

In the study synergy effects in steam co-gasification of energy crops biomass and hard coal blends in terms of chars reactivity variation with blend composition are reported. Fuel reactivity is a parameter indicating its usability in thermochemical process. Higher reactivity enables to use less energy consuming process parameters (e.g. lower temperature and pressure). It depends on many factors, to mention only chemical composition of a fuel and physical and chemical transformations during char formation [23,41–48]. Therefore, the analysis of a potential beneficial changes in reactivity of

chars of fuel blends is relevant and of practical importance in terms of assessment of co-gasification as a prospective clean energy technology.

2. Experimental

2.1. Experimental set-up

The experimental study on co-gasification of coal and biomass was performed in the laboratory fixed bed reactor installation of the Laboratory of Advanced Energy Technologies (see Fig. 1). The installation is composed of a fixed bed reactor of a volume of approximately 0.8 L, heated with a resistance furnace, gasification agents supply system, including oxygen, air and steam, and process gas treatment and measurement system, described in details elsewhere [45].

2.2. Methods

A fuel blend of coal and biomass of a mass of 10 g, dried and of particle size of below 2 mm for coal and below 3 mm for biomass was heated up in an inert gas atmosphere (nitrogen) to the set temperature of 700, 800 or 900 °C with the heating rate of 80 °C/min. Next, steam was injected into the reactor with a flow rate of 3.2 mL/min.

The process variables adopted were: temperatures of 700, 800, 900 °C, biomass content in a fuel blend (0, 20, 40, 60, 80 and 100%w/w) and kinds of fuels tested: hard coal, biomass of selected energy crops: *Salix viminalis*, *Andropogon gerardi*, *Spartina pectinata*, *Miscanthus X giganteus*, *Helianthus tuberosus* and *Sida hermaphrodita*.

The main components of dried and cooled gas were determined with application of two-channel gas chromatograph Agilent 3000A with a PLOT U column ($8 \cdot 10^{-3} \times 0.32 \cdot 10^{-3}$ m) with thermal conductivity detector (TCD) for carbon dioxide and other compounds of 2 ÷ 5 carbon atoms in a molecule and analytical column MS5A PLOT ($10 \times 0.32 \cdot 10^{-3}$ m) with thermal conductivity detector (TCD) for determination of hydrogen, nitrogen, carbon monoxide and methane content in a product gas. The gas flow rate was measured with a flow meter. The volumes of main gas components: hydrogen, carbon monoxide, carbon dioxide,

methane in particular tests V_c , were calculated from the Equation (1):

$$V_c = \sum_{i=1}^n \frac{C_{ci} F_i}{100} t_i \quad (1)$$

where:

V_c – volume of c-th gas component generated during the test, Nm^3

C_{ci} – volume content of c-th gas component in i-th time interval, %vol.

F_i – total gas flow rate in i-th time interval, Nm^3/s

t_i – duration of the i-th time interval, s

n – number of time intervals during a test.

The number (19) of time intervals of 192 s was equal for all experiments and resulted from the settings of the chromatographic method.

Fuel chars reactivity for 50% of carbon conversion, R_{50} , and maximum reactivity, $R_{\max}$, as well as time of reaching 50% of carbon conversion and maximum reactivity, t_{50} and $t_{\max}$ were determined according to the procedure developed in the Department of Energy Saving and Air Protection of the Central Mining Institute, from the Equation (2) [44]:

$$R_x = \frac{1}{m_0} \left(\frac{dm}{dt} \right)_x \quad (2)$$

where:

R_x – reactivity of solid fuel/char for X% of carbon conversion, $1/\text{s}$

m_0, m – initial amount of carbon in a sample (fixed carbon) and in gasification products, respectively, mol

t_x – time of reaching X% carbon conversion, s

X – carbon conversion: $X = m/m_0 \cdot 100$, %.

2.3. Materials

Biomass samples of selected energy crops: (1) *S. viminalis*, (2) *A. gerardi*, (3) *H. tuberosus*, (4) *S. hermaphrodita*, (5) *M. giganteus* and (6) *S. pectinata* were provided from experimental stands (1) of M&D Farms Sp. z o.o. in Świerczów, Poland (2 ÷ 4, 6), Department of Agricultural Sciences in Zamość of University of Life Sciences in Lublin, Poland and (5) plantation in Föhren, Germany. Hard coal (sample no 7) was acquired from Piast coal mine, coal seam 208, heading 1291, according the relevant standard in force (PN-90/G-04502).

The energy crops were selected based on the criteria of yielding levels and suitability for cultivation in local conditions in terms of climate, soil quality, available land area, etc. [49–52]. The proximate and ultimate analyses were performed in the accredited laboratory of the Department of Solid Fuel Quality Assessment of the Central Mining Institute according to the relevant standards in force and testing procedures of the department (PB):

- Analytical moisture content: PN-G-04560:1998 and PB-4, ed. 11, with application of automatic thermogravimetric analyzers LECO: TGA 701 or MAC 500,

- Ash content: PN-G-04560:1998 and PB5, ed. 11, with application of automatic thermogravimetric analyzers LECO: TGA 701 or MAC 500,
- Volatiles: PN-G-04516:1998 and PB-6, ed. 11, based on PN ISO-562:2000 with application of automatic thermogravimetric analyzers LECO: TGA 701 or MAC 500,
- Heat of combustion and calorific value: PN-G-04513:1981 and PB-7, ed. 11, with application of calorimeters LECO: AC-600 and AC-350,
- Total sulfur content: PN-G-04584:2001 and PB-15, ed. 11, with application of TruSpec S analyzer,
- Carbon, hydrogen and nitrogen contents: PN-G-04571:1998 and PB-19, ed. 11, with application of TruSpecCHN analyzer,
- Oxygen content calculated as: $100\% - W^a - A^a - C^a_t - H^a_t - S^a_c$ (PN-G-04510:1991), and fixed carbon as: $100\% - W^a - A^a - V^a$ (PN-G-04516:1998).

Ash composition of tested fuels was determined according to the testing procedure SC-1/PB-05 based on the standard PN-EN ISO 12677 in the accredited Laboratory of Solid Waste Analyses of the Department of Environmental Engineering of the Central Mining Institute with application of Wavelength Dispersive X-ray Fluorescence (WDXRF). The results of the analyses are given in Table 1.

Based on the chemical composition of the fuels tested the following chemical formulas of tested samples were determined: $\text{CH}_{1.43}\text{O}_{0.51}$ (1), $\text{CH}_{1.70}\text{O}_{0.36}$ (2), $\text{CH}_{1.45}\text{O}_{0.57}$ (3), $\text{CH}_{1.44}\text{O}_{0.57}$ (4), $\text{CH}_{1.47}\text{O}_{0.44}$ (5), $\text{CH}_{1.47}\text{O}_{0.58}$ (6), $\text{CH}_{0.70}\text{O}_{0.14}$ (7). The main differences in composition between coal and biomass samples were observed in terms of H/C and O/C ratios, which is presented graphically in Fig. 2 [53].

Fixed carbon content was approximately three times higher for coal than for biomass samples. Content of volatiles in biomass was twice the amount in coal, and of oxygen almost three times higher than in coal. Biomass was also characterized by higher hydrogen content and lower content of sulfur than coal.

Significant differences were also observed in terms of ash content and composition (see Table 1 and Fig. 3). Ash content in coal is higher than in biomass but it includes significantly less alkali and alkali earth metals. These compounds create operational problems when biomass gasification is considered, but may also demonstrate potential catalytic effects in co-gasification process.

3. Results and discussion

Reactivity of coal, biomass and fuel blends chars was determined in a laboratory scale fixed bed reactor installation described in Section 2.1 according to the procedure given in Section 2.2. The results are presented in Figs. 4 and 5.

The lowest values of reactivity for 50% carbon conversion, R_{50} , were observed for coal chars irrespective of process temperature and amounted to $1.98 \cdot 10^{-4}$, $2.31 \cdot 10^{-4}$ and $2.56 \cdot 10^{-4}$ $1/\text{s}$ at 700, 800 and 900 °C, respectively. The highest values of reactivity R_{50} at 700 °C were reported for chars of fuel blends of 40%w/w content of *A. gerardi*, *H. tuberosus* and *M. giganteus* biomass ($2.97 \cdot 10^{-4}$, $4.77 \cdot 10^{-4}$ and $4.09 \cdot 10^{-4}$ $1/\text{s}$,

Table 1 – Characteristics of tested samples of coal and biomass.

Parameter, unit	Sample no. ^a						
	1	2	3	4	5	6	7
Moisture W ^a , %w/w	4.74	9.72	8.81	8.76	6.78	8.69	6.02
Ash A ^a , %w/w	1.51	3.87	3.18	2.63	1.6	4.31	5.69
Volatiles V ^a , %w/w	73.16	70.26	69.24	71.47	76.00	69.89	31.12
Heat of combustion Q _s ^a , J/g	18,171	16,132	15,989	16,484	16,546	16,920	28,805
Calorific value Q _t ^a , J/g	16,697	14,242	14,543	15,030	14,942	15,481	27,616
Total sulfur S _t ^a , %w/w	0.05	0.06	0.04	0.04	0.05	0.12	0.50
Carbon C _t ^a , %w/w	52.19	53.3	46.62	47.18	53.71	45.77	70.64
Hydrogen H _t ^a , %w/w	6.22	7.57	5.64	5.68	6.59	5.62	4.08
Nitrogen N ^a , %w/w	0.00	0.00	0.00	0.00	0.00	0.00	0.98
Oxygen O ^a , %w/w	35.29	25.54	35.74	35.73	31.27	35.58	13.07
Fixed carbon, %w/w	20.59	16.15	18.77	17.14	15.62	17.11	57.17
SiO ₂ , %w/w (in ash)	14.67	65.18	32.54	3.65	69.01	64.82	46.55
Al ₂ O ₃ , %w/w (in ash)	3.18	0.45	1.24	0.64	0.38	0.33	25.65
Fe ₂ O ₃ , %w/w (in ash)	0.93	0.28	0.52	0.28	0.19	0.32	8.63
CaO, %w/w (in ash)	37.10	11.74	34.20	42.43	15.27	9.99	7.34
MgO, %w/w (in ash)	3.46	3.60	2.94	4.66	1.79	1.50	3.82
Na ₂ O, %w/w (in ash)	0.53	0.93	1.02	1.75	0.73	1.53	2.60
K ₂ O, %w/w (in ash)	22.13	7.26	12.93	21.77	2.98	11.48	1.92
SO ₃ , %w/w (in ash)	4.12	3.85	5.90	5.56	4.95	4.95	1.78
TiO ₂ , %w/w (in ash)	0.15	0.06	0.08	0.05	0.05	0.05	1.08
P ₂ O ₅ , %w/w (in ash)	13.17	5.97	7.87	17.30	3.99	4.45	0.36
ZnO, %w/w (in ash)	0.00	0.00	0.00	1.07	0.00	0.00	0.00

^a 1 – *Salix viminalis*, 2 – *Andropogon gerardi*, 3 – *Helianthus tuberosus*, 4 – *Sida hermaphrodita*, 5 – *Miscanthus X giganteus*, 6 – *Spartina pectinata*, 7 – hard coal.

respectively) and of 20%w/w content of *S. viminalis*, 60%w/w content of *S. pectinata* and chars of *S. hermaphrodita* biomass ($3.31 \cdot 10^{-4}$, $4.10 \cdot 10^{-4}$ and $4.21 \cdot 10^{-4}$ 1/s, respectively).

At 800 °C, the highest values of reactivity R_{50} were observed for chars of fuel blends containing 40%w/w of *H. tuberosus* and *S. pectinata* biomass ($4.99 \cdot 10^{-4}$ and $4.8 \cdot 10^{-4}$ 1/s, respectively) and 60%w/w of *A. gerardi*, 80%w/w of *M. giganteus* and char of *S. hermaphrodita* biomass ($4.53 \cdot 10^{-4}$, $4.41 \cdot 10^{-4}$ and $4.75 \cdot 10^{-4}$ 1/s, respectively). In case of chars of *S. viminalis* blends, the highest value of reactivity R_{50} at 800 °C, amounting to $4.13 \cdot 10^{-4}$ 1/s, was reported for chars of fuel blends of 20% and 40%w/w biomass content.

The highest values of reactivity R_{50} at 900 °C were reported for chars of fuel blends of 40%w/w content of *S. hermaphrodita*

and *M. giganteus* ($5.39 \cdot 10^{-4}$ and $4.84 \cdot 10^{-4}$ 1/s, respectively), 60%w/w of *A. gerardi* and *S. pectinata* ($4.56 \cdot 10^{-4}$ and $4.91 \cdot 10^{-4}$ 1/s, respectively) and 80%w/w of *S. viminalis* and *H. tuberosus* biomass ($4.84 \cdot 10^{-4}$ and $5.43 \cdot 10^{-4}$ 1/s, respectively) (see Fig. 4).

The chars with a content of *H. tuberosus* biomass were characterized by the highest values of reactivity R_{50} at each process temperature: $4.77 \cdot 10^{-4}$ 1/s at 700 °C (40%w/w), $4.99 \cdot 10^{-4}$ 1/s at 800 °C (40%w/w) and $5.43 \cdot 10^{-4}$ 1/s at 900 °C (80%w/w). High reactivity R_{50} , irrespective of process temperature, was also characteristic for chars of fuel blends containing *S. hermaphrodita* biomass: $4.21 \cdot 10^{-4}$ 1/s at 700 °C (biomass char), $4.75 \cdot 10^{-4}$ 1/s at 800 °C (biomass char) and $5.39 \cdot 10^{-4}$ 1/s at 900 °C (char of a fuel blend of 40%w/w biomass content) and *S. pectinata* biomass: $4.10 \cdot 10^{-4}$ 1/s at 700 °C (60%

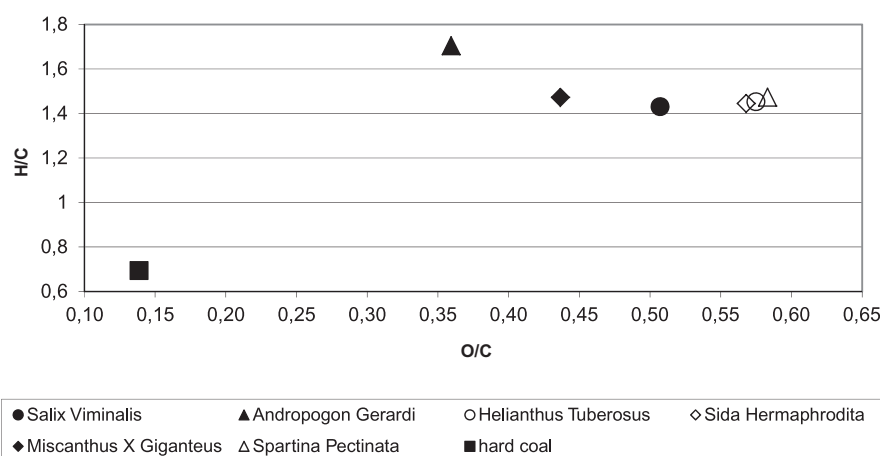


Fig. 2 – Van Krevelen diagram for tested fuel samples: 1 – *Salix viminalis*, 2 – *Andropogon gerardi*, 3 – *Helianthus tuberosus*, 4 – *Sida hermaphrodita*, 5 – *Miscanthus X giganteus*, 6 – *Spartina pectinata*, 7 – hard coal.

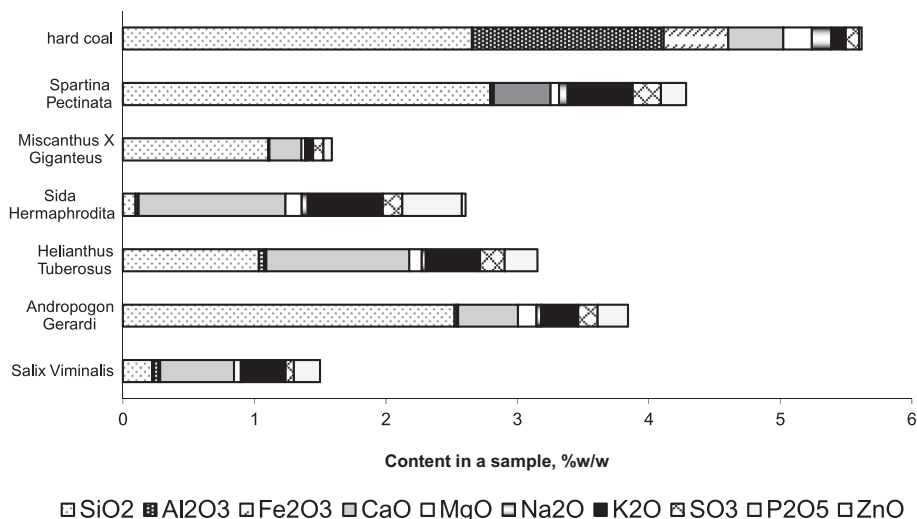


Fig. 3 – Composition of ash of samples tested: 1 – *Salix viminalis*, 2 – *Andropogon gerardi*, 3 – *Helianthus tuberosus*, 4 – *Sida hermaphrodita*, 5 – *Miscanthus X giganteus*, 6 – *Spartina pectinata*, 7 – hard coal.

w/w), $4.80 \cdot 10^{-4}$ 1/s at 800 °C (40%w/w) and $4.91 \cdot 10^{-4}$ 1/s at 900 °C (60%w/w). At 800 °C also chars of a fuel blend of 60%w/w of *S. pectinata* biomass content were characterized by relatively high reactivity, R_{50} , amounting to $4.63 \cdot 10^{-4}$ 1/s (see Fig. 4).

The maximum values of reactivity R_{50} reported for chars containing biomass of particular energy crops increased with temperature from 700 to 900 °C. Similarly, for chars of particular fuel blends (in terms of biomass kind and content), the reactivity increased with temperature, except for: chars of fuel blends with *H. tuberosus* content (20 ÷ 60%w/w) at 900 °C (decrease in R_{50} value in comparison with the value reported at 800 °C) and 80%w/w at 800 °C (decrease in R_{50} value when compared to the one at 700 °C); chars of fuel blends containing *S. hermaphrodita* biomass (20 and 40%w/w) at 800 °C; chars of fuel blends of 80%w/w *M. giganteus* biomass content at 900 °C and chars of fuel blends of 20 and 40%w/w of *S. pectinata* biomass content at 900 °C (see Fig. 4).

The reactivity reported for chars of fuel blends were higher than those for biomass chars irrespective of the temperature (except for *S. hermaphrodita* at 700 and 800 °C), which is in line with the observations [23,33–36], and [26–28,31,32] and results basically from the differences in structure and composition of coal and biomass. Coal is structured mainly by chemical bonds of approximately $1 \cdot 10^6$ J/mol, while cellulose and lignin present in biomass contain mainly ether bonds of approximately $0.38 \cdot 10^6$ ÷ $0.42 \cdot 10^6$ J/mol [35,36]. Thermal breaking of weak bonds of organic substance of biomass releases volatiles, which are easily decomposed to form free radicals, which further reacts with organic substance of coal and biomass. Also hydrogen generated in thermal decomposition of light products of devolatilization may react with coal-derived free radicals, which prevents recombination reactions and creation of less reactive, secondary chars [34]. Furthermore, since lower rank coals are more reactive than high rank coals, also the biomass tested, which contains 30% less carbon than coal, was proved to be more reactive [54]. The highest values of reactivity R_{50} were reported for chars of fuel blends

including *H. tuberosus*, *S. hermaphrodita* and *S. pectinata* of the lowest content of carbon among the tested biomass samples: 46.62, 47.18 and 45.77%w/w, respectively. Furthermore, alkali and alkali earth compounds, including potassium, calcium and sodium are claimed to influence chars reactivity in the gasification process [34,55,56]. This is supported by the results reported: the highest content of potassium and calcium oxides in the samples tested was observed for *H. tuberosus*: 1.09% w/w of CaO and 0.41%w/w of K_2O , *S. hermaphrodita*: 1.12%w/w of CaO and 0.57%w/w of K_2O and *S. pectinata*: 0.43%w/w of CaO and 0.49%w/w of K_2O (see Fig. 3).

Time of reaching 50% of carbon conversion, t_{50} , at 700 °C was the shortest for chars of fuel blends of coal and biomass of *H. tuberosus*, *S. hermaphrodita* and *S. pectinata* and amounted to 960 ÷ 1152 s. Chars of fuel blends containing biomass of *A. gerardi* and *M. giganteus* varied from 1152 to 1344 s, and of *S. viminalis* from 1344 to 1536 s. The highest value of t_{50} , 2304 s, was observed for *S. viminalis* char.

The respective values at 800 °C for chars of fuel blends of coal and biomass of *H. tuberosus*, *S. hermaphrodita* and *S. pectinata* were 960 ÷ 1152 s. Chars of the remaining fuel blends were characterized by t_{50} values of 768 ÷ 1344 s (*M. giganteus* blends), 768 ÷ 1536 s (*A. gerardi* blends) and 960 ÷ 1344 s (*S. viminalis* blends).

Similar values of t_{50} for chars of fuel blends of *H. tuberosus*, *S. hermaphrodita* and *S. pectinata* were reported at 900 °C: 768 ÷ 1152 s. Chars of fuel blends of coal and *M. giganteus* biomass were characterized by t_{50} value of 960 s, and of *A. gerardi* and *S. viminalis* of the values ranging from 960 to 1152 s and from 960 to 1728 s, respectively.

The highest values of reaching 50% of carbon conversion, t_{50} , were observed for coal chars irrespective of process temperature: 1536 s at 700 and 900 °C, and 1728 s at 800 °C.

The lowest values of R_{max} irrespective of process temperature were reported for coal chars: $3.73 \cdot 10^{-4}$, $4.68 \cdot 10^{-4}$ and $4.45 \cdot 10^{-4}$ 1/s at 700, 800 and 900 °C, respectively (see Fig. 5). The highest values of R_{max} at 700 °C were observed for chars of fuel blends of coal and 20% and 40%w/w of *S. viminalis*

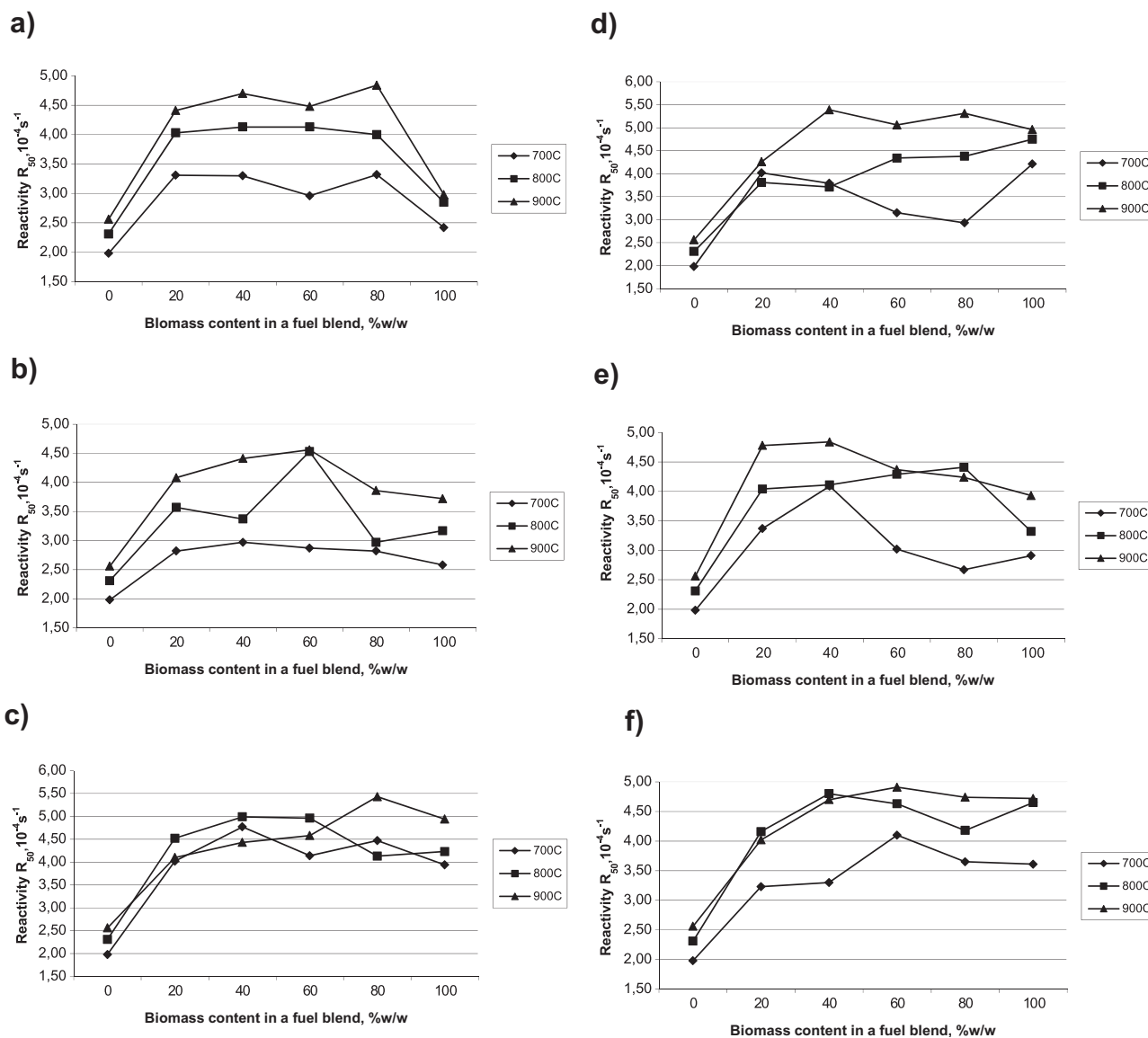


Fig. 4 – Reactivity of chars of fuel blends tested R_{50} vs biomass content in a fuel blend in steam gasification: a) *Salix viminalis*, b) *Andropogon gerardi*, c) *Helianthus tuberosus*, d) *Sida hermaphrodita*, e) *Miscanthus X giganteus*, f) *Spartina pectinata*.

($5.97 \cdot 10^{-4}$ and $6.17 \cdot 10^{-4}$ 1/s, respectively) and *A. gerardi* biomass ($6.60 \cdot 10^{-4}$ and $6.58 \cdot 10^{-4}$ 1/s, respectively). Among the remaining chars the highest values were reported for chars of a fuel blend of 60%w/w of *H. tuberosus* biomass content ($6.96 \cdot 10^{-4}$ 1/s), 60%w/w and 100%w/w of *S. hermaphrodita* biomass content ($6.87 \cdot 10^{-4}$ and $6.91 \cdot 10^{-4}$ 1/s, respectively), 80%w/w of *M. giganteus* biomass content ($6.07 \cdot 10^{-4}$ 1/s) and 80%w/w of *S. pectinata* biomass content and *S. pectinata* biomass chars ($6.47 \cdot 10^{-4}$ and $6.94 \cdot 10^{-4}$ 1/s) (see Fig. 5).

At 800 °C, the highest values of $R_{\max}$ were observed for chars of fuel blends containing 60%w/w of *S. viminalis*, *H. tuberosus*, *S. hermaphrodita* and *S. pectinata* biomass ($6.67 \cdot 10^{-4}$, $7.85 \cdot 10^{-4}$, $6.70 \cdot 10^{-4}$ and $7.67 \cdot 10^{-4}$ 1/s, respectively), and 80%w/w of *A. gerardi* and *M. giganteus* biomass ($7.99 \cdot 10^{-4}$ and $7.44 \cdot 10^{-4}$ 1/s, respectively).

The highest values of $R_{\max}$ at 900 °C were reported for chars of fuel blends of 40%w/w of *A. gerardi* biomass content

($8.24 \cdot 10^{-4}$ 1/s), 80%w/w of *S. viminalis*, *H. tuberosus* and *S. hermaphrodita* biomass content ($7.65 \cdot 10^{-4}$, $7.40 \cdot 10^{-4}$ and $7.57 \cdot 10^{-4}$ 1/s) and *M. giganteus* and *S. pectinata* biomass chars ($7.26 \cdot 10^{-4}$ and $7.89 \cdot 10^{-4}$ 1/s).

Relatively high values of $R_{\max}$ were observed for chars of fuel blends containing *H. tuberosus* ($6.96 \cdot 10^{-4}$, $7.85 \cdot 10^{-4}$ and $7.40 \cdot 10^{-4}$ 1/s, at 700, 800 and 900 °C, respectively), *S. pectinata* ($6.94 \cdot 10^{-4}$, $7.67 \cdot 10^{-4}$ and $7.89 \cdot 10^{-4}$ 1/s) and *S. hermaphrodita* biomass ($6.87 \cdot 10^{-4}$, $6.70 \cdot 10^{-4}$ and $7.57 \cdot 10^{-4}$ 1/s), irrespective of process temperature.

Time of reaching the maximum reactivity, $t_{\max}$, at 700 °C varied from 192 to 576 s for chars of fuel blends of coal and biomass of *S. viminalis*, *A. gerardi* and *S. hermaphrodita* and from 192 to 768 s for chars containing biomass of *H. tuberosus* and *M. giganteus*. Chars of fuel blends with content of *S. pectinata* biomass were characterized by the $t_{\max}$ value of 384 s.

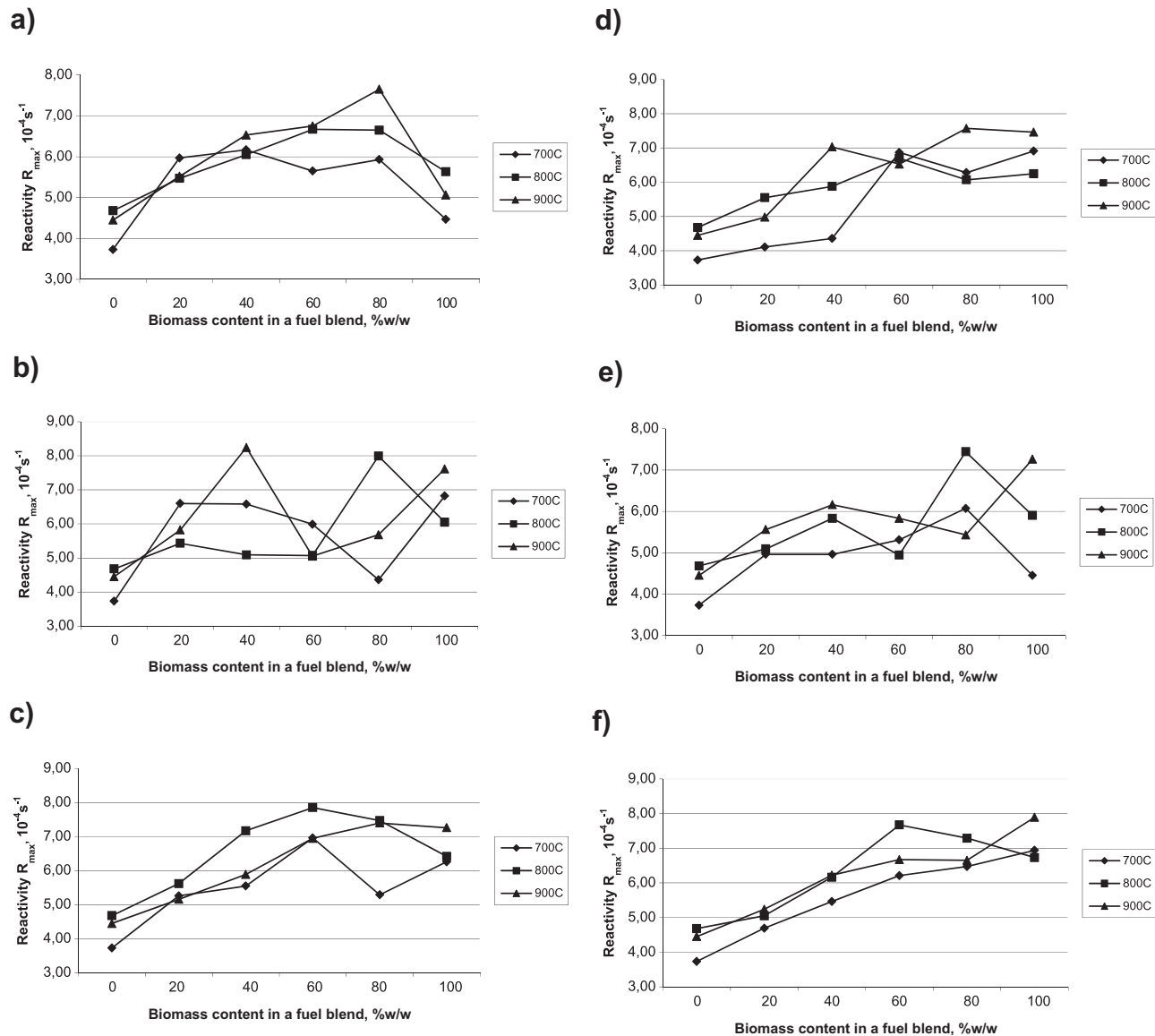


Fig. 5 – Reactivity of chars of fuel blends tested $R_{\max}$ vs biomass content in a fuel blend in steam gasification: a) *Salix viminalis*, b) *Andropogon gerardi*, c) *Helianthus tuberosus*, d) *Sida hermaphrodita*, e) *Miscanthus X giganteus*, f) *Spartina pectinata*.

At the temperature of 800 °C values of $t_{\max}$ varied from 192 to 576 s for chars of fuel blends of coal and *S. viminalis*, *A. gerardi* and *H. tuberosus* biomass; from 192 to 384 s for chars of fuel blends including *M. giganteus* and *S. pectinata* biomass and from 384 to 768 s for *S. hermaphrodita* fuel blends chars.

At 900 °C the values of $t_{\max}$ for chars of fuel blends with *S. viminalis*, *A. gerardi*, *S. hermaphrodita* and *M. giganteus* varied in the range of 192 ÷ 384 s (except for the char of a fuel blend of 20%w/w of *S. hermaphrodita* biomass content: 768 s), and for chars containing biomass of *H. tuberosus* and *S. pectinata* it equaled 384 s.

4. Conclusions

The results of the study presented in the paper enabled to draw the following conclusions:

1. The highest values of reactivity R_{50} and $R_{\max}$, in the process of steam co-gasification, within the tested parameters range, were reported for chars of fuel blends of coal and biomass of *H. tuberosus*, *S. hermaphrodita* and *S. pectinata*, of the lowest carbon content and the highest concentration of potassium and calcium oxides among the biomass samples tested.
2. Increase in chars reactivity for 50% of carbon conversion, R_{50} , was observed when compared to values for biomass chars (except for chars of fuel blends containing *S. hermaphrodita* biomass at 700 and 800 °C) and in maximum reactivity, $R_{\max}$, (except for chars of fuel blends of coal and *S. hermaphrodita* and *S. pectinata* biomass at 700 °C and *M. giganteus* and *S. pectinata* at 900 °C). The lowest values of reactivity and the highest of t_{50} characterized chars of coal, irrespective of process temperature.
3. The results prove the synergy effect in the process of co-gasification of coal and biomass of selected energy crops

under the test conditions adopted in terms of increase in reactivity of fuel blend chars when compared to the values reported for coal and biomass chars.

4. Increase in reactivity for 50% of carbon conversion, R_{50} , of the chars tested in co-gasification with increasing process temperature and decreasing carbon content in a fuel was also observed.
5. The process of steam co-gasification of coal and biomass may offer several advantages over the gasification process of coal and biomass separately. These consists in increased stability of fuel supplies, larger scale of installation, CO_2 emission reduction and potential utilization of catalytic properties of compounds naturally present in biomass and influencing the steam gasification process, as alternative to expensive catalysts. The latter requires, however; further detailed studies.

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